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Plasma Characterization for Electrothermal-Chemical (ETC) Gun Applications

by Kevin J. White, Gary L. Katulka,
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Weapons and Materials Research Directorate, ARL

Abstract

Successful application of the electrothermal chemical (ETC) propulsion concept will require an understanding of the propagation and interaction of plasmas in propellant beds. This information is necessary to exploit the ignition and combustion control that is possible with plasmas. Toward this end, an experimental program was designed to gain an understanding of the functioning of the plasma and the interaction of the plasma with the propelling charge, and finally a series of 30-mm gun tests, incorporating the experience gained in the first two parts of the program, was conducted.

This report describes the results of the first two parts of this program. Here results are described of tests on different igniter centercore configurations to be used for distributing the electrical plasma within the combustion chamber. High-speed photographic measurements were made of open air firings (with various centercore designs) and in a 30-mm gun simulator. Propagation velocities along with the time-sequence of events for the functioning in the centercore tubes were recorded. High axial pressure gradients were observed, necessitating mechanically robust centercores. Radiation levels substantially in excess of conventional igniters were also noted. These observations were exploited in the design of a plasma distribution centercore for 30-mm gun tests.

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1. INTRODUCTION

The electrothermal chemical (ETC) propulsion concept has been proposed as a technique for increasing projectile muzzle velocity by enhancing conventional chemical gun performance. The improvement in gun performance was based on two concepts: (a) the electrical energy would supplement the conventional propellant chemical energy, and, (b) since the input of the electrical energy is readily programmed, it could be selectively introduced into the gun chamber to maintain an ideal (flat) pressure profile for a longer time, increasing the muzzle velocity. To test these ideas, ideal interior ballistic calculations were carried out on numerous gun systems to estimate the potential performance gains from employing the electrothermal concept (White, Oberle, and Juhasz 1992). The calculations showed that, using realistic sized power supplies together with standard conventional solid propellant charges, only marginal performance improvement was realized, even under ideal conditions. However, it was discovered that more significant improvement could be achieved by using higher loading density and/or energy charges. In practice, though, the high-loading density charges are difficult to ignite in a reproducible manner with conventional chemical igniters. Moreover, practical propellant grain geometry design limits performance improvement at high-loading densities since the propellant will not burn up prior to muzzle exit (Robbins 1993; White et al. 1994). However, since the electrical energy pulse can be carefully tailored and ignition and flame spreading can be improved because of plasma characteristics such as velocity and temperature, it is believed that electrothermal energy could be used to overcome these difficulties. To capitalize on the potential performance gain offered by ETC concepts with high-loading density solid propellant, an experimental program was initiated to test these concepts.

To properly ignite the propelling charge in a gun chamber, electrical energy, in the form of a plasma, must be introduced into the chamber in an optimized way with respect to time and position. As preliminary tests to gun firings, open-air firings were carried out on various designs of plasma distribution devices such as centercores. High-speed photography and light-detecting diodes were used to determine flow and radiative characteristics of the plasma output. Based on these results, tests were then performed in a 30-mm diagnostic simulator. This simulator allowed for high-speed photographic studies of the interaction of the plasma output with a high-loading density propelling charge. Finally, instrumented gun firings were performed based on the simulator results. The results from these gun tests are discussed in greater detail in a separate report (Stobie et al. 1993).

A schematic of a rear-injected ETC gun system is shown in Figure 1. It has been found over years of ballistic research, that for high-loading density charges, this configuration will lead to localized ignition of the charge with subsequent chamber pressure waves. To avoid this in conventional chemical igniter systems, centercore tubes have been used to distribute the ignition energy throughout the propellant bed. The centercore runs coaxial with the chamber and distributes the energy radially throughout the bed. This general energy distribution concept will be used to introduce the plasma energy into the propellant bed.

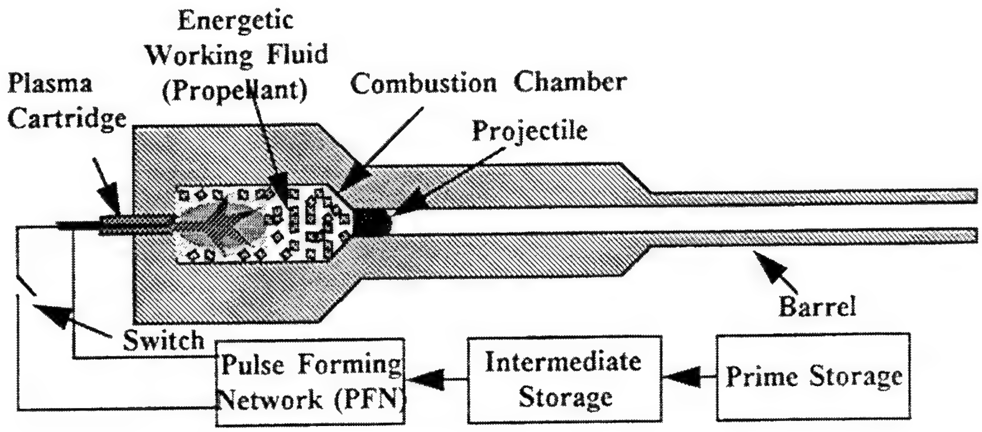


Figure 1. Schematic of rear plasma injected ETC gun.

There are, however, some significant differences between the output from chemical igniters and plasma generators. The products for the former have a temperature on the order of 3,000 K, while the latter are approximately 10,000 K (Beyer and Bunte 1992; Mach et al. 1994). If both are optically dense, the radiative component of the energy is proportional to T^4 (Stobie et al. 1993). Thus, the radiative energy from a plasma may be up to 100 times greater than for a chemical igniter. This radiative component may be important in ignition and should be considered when designing a centercore or any other energy distribution system.

Most centercore tubes used in conventional large-caliber cannons are made of metallic components. However, plastic was chosen as the material for the centercore tube in ETC firings for a number of reasons. First, plastic has a lower thermal conductivity than metal and thus a lower heat loss. Hence, less energy from the plasma would be lost in heating plastic components. Second, if the hot plasma gases cause erosion, it would be better to have hydrocarbon rather than metal products from the centercore tube entering the gun combustion chamber to avoid fouling. Third, the plasma has a large component of radiation energy. If this radiation is important in the subsequent ignition of the propellant, then the plastic

would allow transmission of radiation into the propellant bed. Measurements were made on radiation transmission characteristics of plexiglass, acetate and mylar materials (McNesby 1993).

All of these materials have similar spectral characteristics and the transmission property differences depend principally on material thickness. At thicknesses up to 3.2 mm (1/8 in), over 80% radiation is transmitted at wavelengths from 400 nm up to 1,600 nm. There is a strong absorption from 1,600 nm out to 1,700 nm. Beyond that, the 3.2-mm (1/8-in) material has approximately 40% transmission from 1,700 to 2,100 nm. From 2,100 to 20,000 nm (2.1 to 20 μm), there is very little transmission, except for a small band at 2.7 μm. However, with the acetate/mylar materials (thickness, 76 μm [0.003 in]) there was considerable transmission from the visible out to 7 μm, followed by absorption from 7 to 10 μm and some transmission from 10 to 20 μm. Thus, the transmission characteristics of the longer wave radiation are strongly dependent on the thickness of the plastic material. If radiation is an important mechanism in the propellant ignition process, then the centercore material thickness may have an effect on the ballistic process.

The ultraviolet (uv) transmission characteristics of the materials were not measured. There is, however, a significant amount of uv radiation at 10,000 K from a black body radiator. This could produce photochemical effects in the propellant combustion process. Furthermore, the transmission characteristics of the material at these plasma high-energy densities may also change due to either bleaching effects or chemical changes induced in the plastic by the uv.

The experimental program described in the following sections is directed at understanding and measuring the sequence of events associated with the functioning of the plasma generator by itself, and, additionally, the interaction of the plasma output with a propellant bed using radiation detectors and high-speed photographic techniques. The following sections will include a description of the experimental setup, open-air firings of the plasma generator, firings of the plasma generator with a variety of centercore tubes and finally, firings of the plasma/centercore in a 30-mm gun simulator.

2. EXPERIMENTAL SETUP

The general view of the plasma generator with and without centercore is shown in Figure 2. Because of the large dynamic range of the plasma luminosity, up to four high-speed cameras were used. Two mechanical cameras with color film and one or two electronic cameras were operated at different framing

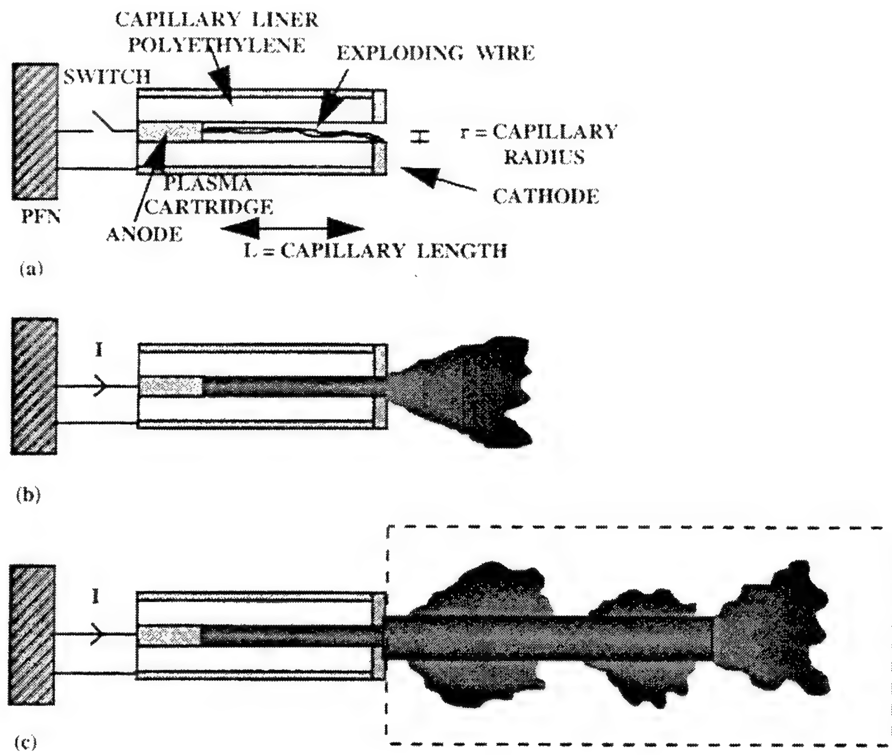


Figure 2. <u>(a) Schematic of plasma generator, (b) open-air firing, (c) with centercore.</u>

rate speeds, viewing areas, and apertures. To orient the reader, Figure 2 is the general view angle of all photographs that will be shown in this report. The photographic results complemented each other as they recorded different aspects of the plasma output.

A witness plate was placed beyond the end of the centercore tube, perpendicular to the axis of the centercore. Combustible material could be mounted on this plate to see the effects of radiation and convective flow output from the centercore tube. In some instances, combustible material was mounted axially on the centercore tube itself to monitor combustion events.

Camera No. 1 was a general purpose, high-speed framing camera. Its field of view included the centercore tube and some distance down from the tube, including the witness plate. This camera was run at a nominal speed of 5,000 pictures/s (interframe time, 200 µs; shutter speed, 80 µs).

Camera No. 2 (for most tests, a one-half frame camera) was run at a nominal speed of 14,000 pictures/s (interframe time, 70 µs; shutter speed, 28 µs). A lens was chosen to include only the first 15–20 cm beyond the output of the plasma, which was mainly the centercore tube (see dotted outline

in Figure 2c). The plasma luminosity was extremely bright, and an optical density filter of 2 (providing an attenuation of 100) with a lens aperture of f/22 was required to keep from overexposing the pictures, even at 14,000 pictures/s.

Camera No. 3, a Cordin electronic camera that records three pictures at any predetermined time interval, was setup with a shutter speed of 500 ns (OD = 3, f/16) in an effort to freeze the plasma motion. The interframe time of the three pictures was adjusted to record data that could be used to measure propagation velocity.

Camera No. 4, an EEV electronic camera, was setup in a manner similar to the Cordin camera. However, due to equipment malfunction, only one picture was taken for each test. This camera was not used for some of the later tests.

Silicon photodiodes were used to record the total radiation output from the test. A model S1336BQ was used that has a sensitivity range from 190 to 1,100 nm. Thus, uv, visible, and ir radiation were recorded. For later tests, a GaAsP photodiode (G1116) was also used. It has a sensitivity range from 300 to 680 nm, allowing the differentiation of the uv, visible, and ir radiative components of the plasma tube.

The electrical power supplied to the plasma generator was supplied by a five-stage, pulse-forming network (PFN) that could store up to 130 kJ (Figure 3). The five stages could be charged to different voltages and fired at different times to obtain the desired power pulse shape. The electrical data were recorded using a Rogowski coil for load current and a voltage divider and current transformer for load voltage. These data were used to generate load current, voltage, power, energy, and impedance as a function of time. The power input to the load will be presented for some tests in this report.

In general, three types of pulses were used: a low-energy short pulse (6 kJ, 20 MW), a high-energy short pulse (50 kJ, 200 MW), and a high-energy long pulse (40 kJ, 90 MW). Examples of these will be given in succeeding sections. The first discussion will be on open-air firings (i.e., firings of the plasma without any centercore tubes [Figure 2b]). This will be followed by a discussion of firings using a large acrylic centercore tube (Figure 2c). Next will be a discussion using 12.5-mm centercore tubes consisting of acetate material and also of polyethylene material. Finally, a description will be given of firings carried out in a 30-mm simulator using a mixture of live and inert propellant.

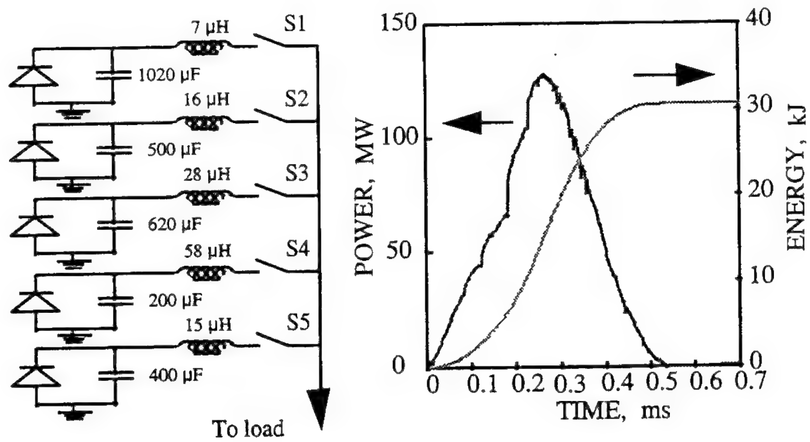
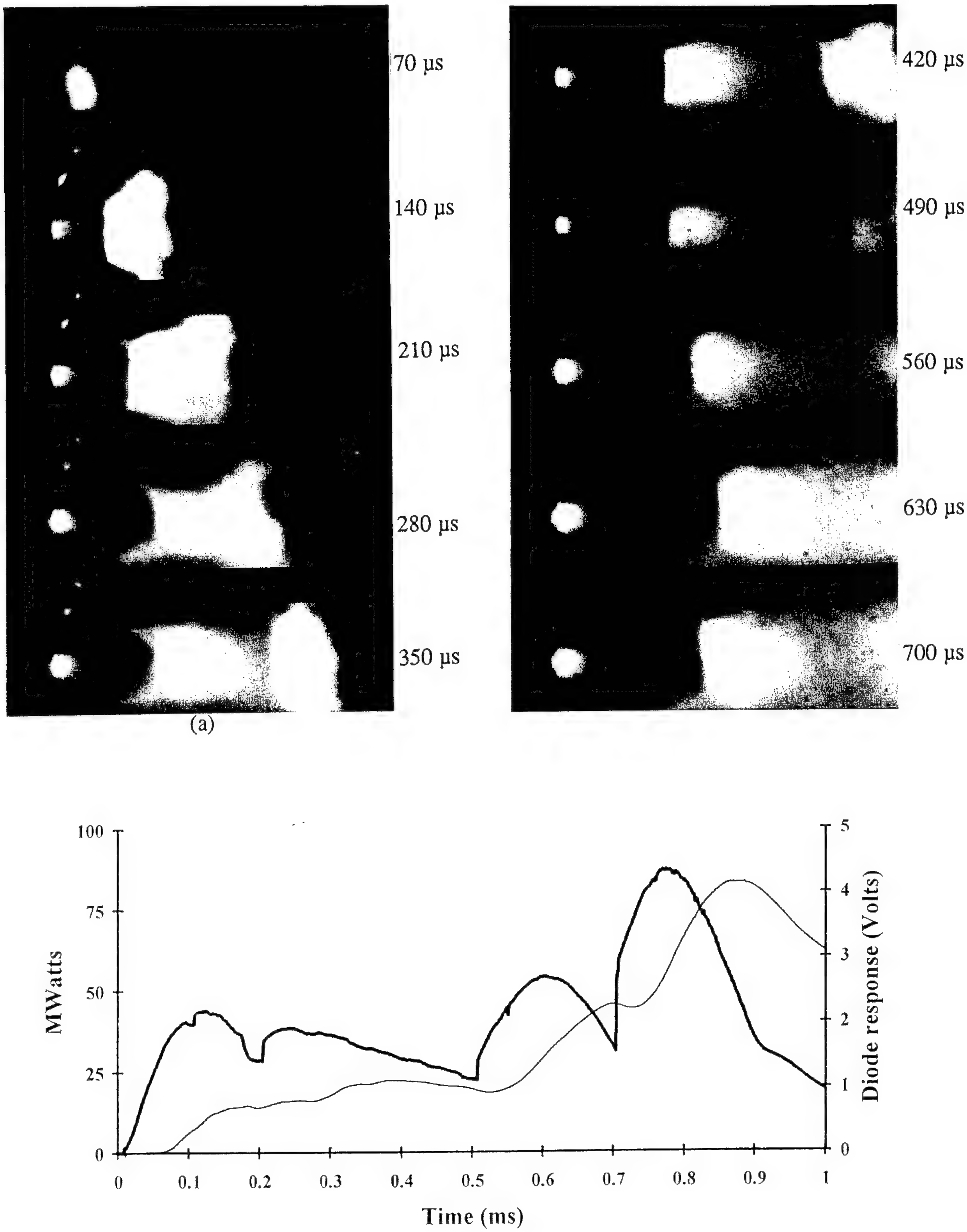


Figure 3. Five-stage pulse-forming network and sample electrical pulse.

3. OPEN-AIR FIRINGS

The purpose of these tests was to characterize the output of the plasma generator without any centercore or propellant chamber. The view of the plasma tube as seen by the cameras is shown in Figure 2b. As was mentioned, each camera had a different field of view of the plasma output. The sequence of pictures (70 μs between pictures) for the output is shown in Figures 4a and 4b. Figure 4c shows the corresponding plasma power curve and diode response. The flow pattern is typical of an underexpanded free jet. There is a sudden cooling of the jet as it emerges from the nozzle just beyond the conical region. As the gases pass through the compression waves, they are reheated. This is seen in the bright illumination down stream in pictures at 140, 210, and 280 μs (time between pictures 70 μs). The shock wave continues to expand and weaken as time goes on and as the electrical power drops off, as seen in Figure 4c. As the last stage fires at approximately 700 μs, an increase is observed in the plasma brightness (10th frame) and the shock wave moves further down stream.

Looking at the power curve and the diode response, it is seen that there is approximately a 70–80 μs delay in the response of the diode. It should be remembered that the power is measured at the input to the plasma generator, but the diode and cameras are observing the output of the plasma generator. This 70–80 μs is believed to be the conversion time from electrical energy to plasma radiative output. Note also that the diode has the same general shape as the power curve, including the increase at 700 μs when



(c)

Figure 4. Open-air ID 091793, (a) frames 1–5, (b) frames 6–10, (c) plasma power and diode response vs. time.

the last stage of the PFN was turned on. This delay was observed for all four open-air tests shown in Table 1.

Table 1. Open-Air Tests

ID	Centercore			Energy	Power	Comment
	OD (mm)	thickness (mm)	length (mm)	load (kJ)	peak (MW)	
012793,2	open air	n/a	n/a	—	—	no control tube, low E
042093,1	open air	n/a	n/a	~7	~24	open air for efficiency base line
042093,2	open air	n/a	n/a	38	147	open air for eff. base line, high E
091793,1	open air	n/a	n/a	42	87	long, hi E pulse

4. LARGE ACRYLIC CENTERCORE TUBES

Early in the program it was not evident as to what type of centercore tube (Figure 2c) would be adequate for use in a gun system. Consequently, relatively large, clear acrylic tubes (OD = 32 mm [1.5 in], wall = 3 mm [1/8 in]) were used (described in Table 2). This was a compromise between strength and radiation transmission characteristics. These tubes remained intact out to 1–2 ms, long after the plasma energy front had propagated through the tube. However, the tube failed later in time and the rupture of the tube always took place at the rear most section, indicating an axial pressure gradient within the tube.

Table 2. Large Acrylic Centercore Tubes

ID	Centercore			Energy	Power	Comment
	OD (mm)	thickness (mm)	length (mm)	load (kJ)	peak (MW)	
122192,1	32	3.2	150	—	—	1 1/4-in acrylic tube, low E
122492,1	32	3.2	150	6.5	20.0	1 1/4-in acrylic tube, low E
011193,1	32	3.2	150	5.8	20.1	1 1/4-in acrylic tube, low E
012093,1	12.5	3.2	140	5.4	20.5	1/2-in acrylic tube, low E
012893,1	19	1.6	146	6.2	21.2	3/4-in acrylic tube, low E
012993,1	19	1.6	711	6.5	21.7	3/4x28-in acrylic tube, low E

Propagation velocity measurements were made for a number of different powers for the *leading* edge of the plasma as it moved down the centercore. Measured from the film records, this velocity appeared to be approximately 1,800 m/s.

To test the effect of the convective and radiative component of the plasma as an ignition device, combustible materials such as tissue paper and JA2 propellant sheets were placed both on the surface of the acrylic tube and on the witness plate located perpendicular to the axis of the tube (see Figure 5a, frames 2 and 3). The material on the tube surface would be subject to radiative energy only. Those located on-axis, approximately 10 cm from the end of the acrylic tube, would be subjected to both the radiative output and convective flow from the plasma generator. To separate the two effects, one of the two adjacent pieces of the combustible material was covered with a thin (0.1 mm, 0.004 in) mylar layer protecting it from the (axial) convective flow, but allowing the radiation to reach the sample. The other piece was left uncovered, subjecting it to both the radiative and convective flow. These samples were unconfined. In no case, listed in Table 2, was there any evidence of reaction taking place with any of the samples, be they tissue paper or propellant. As is seen in Table 2, the energy and power used in these experiments was relatively low compared with that used in most gun experiments that usually employ anywhere from hundreds of kilojoules to megajoules.

Although these acrylic tubes seemed to be relatively durable and allowed for a measurement of propagation velocity, they were too large to be considered for application in a 30-mm system. They would consume too much volume in the gun chamber, limiting the ability to reach high-loading densities.

5. CENTERCORE TUBES, 12.5-mm (1/2 in) OUTSIDE DIAMETER

5.1 Acetate Centercore, 0.1-mm (0.004 in) Wall Thickness. As was discussed in an earlier section, the radiation transmission characteristics of the plastic centercore material depends on the thickness, especially in the infrared spectral region. A thin acetate film (0.1 mm [0.004 in]) was chosen for its high radiation transmission properties and its low mass. Such a centercore material would minimize heat loss and residue left behind in the chamber after a gun firing.

Thus, a 12.5-mm (1/2 in) diameter cylinder was made from the thin acetate film. The seam was closed by heat-sealing with a soldering iron and then reinforced with epoxy. In some cases, the cylinder was reinforced with a helix of 134 N (30-lb) test nylon single strand cable.

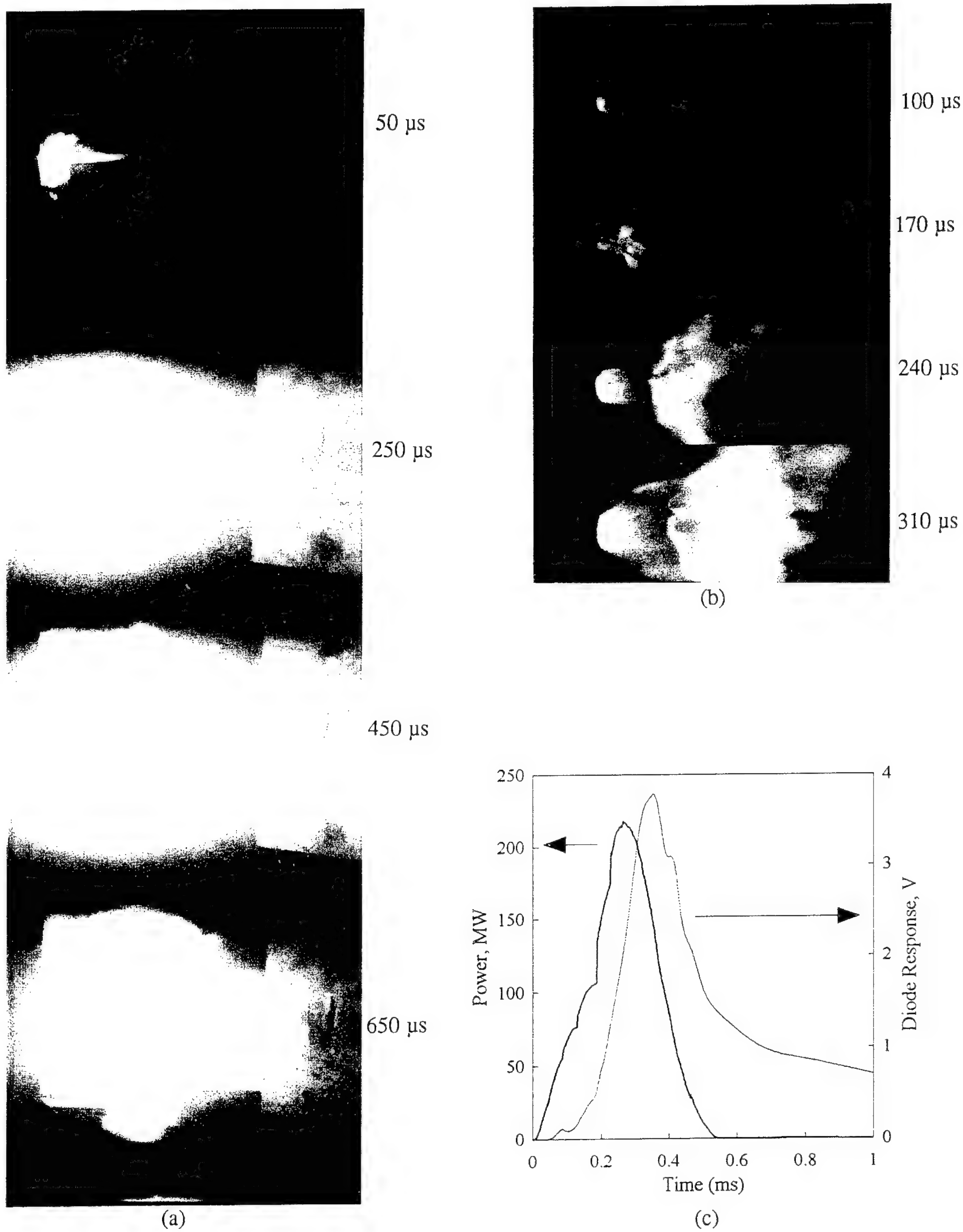


Figure 5. Acetate centercore, ID 051193, (a) 5,000 pps, (b) 14,000 pps, (c) plasma power and diode response vs. time.

Table 3 gives a summary of conditions for firing with this configuration. An example of the photographic results from a test firing is seen in Figure 5, along with power and diode response data. Examination of the high-speed film records indicated that none of the tubes remained intact for more than 170 µs (Figure 5b). Rupturing took place at the base where the centercore joins up with the plasma generator (Figure 2c). Additionally, post-firing examination of the centercore also revealed that rupturing took place at the rear. The remainder of the cylinder was largely intact.

Table 3. Acetate Centercore

ID	Centercore			Energy	Power	Comment
	OD (mm)	thickness (mm)	length (mm)	load (kJ)	peak (MW)	
012793,1	12.5	0.1	150	7.4	24.3	acetate, 1/2-in unreinforced, low E
012893,2	12.5	0.1	152	6.5	20.9	acetate, 1/2-in unreinforced, low E
050393,2	12.5	0.1	203	51.3	214	acetate reinforced, high E, <70 µs
051193,1	12.5	0.1	203	52	217	acetate reinforced, high E, epoxy to anode

Later tests with reinforcing materials did not improve performance. An attempt was made to use this configuration in a 30-mm test fixture (White et al. 1994) using a granular propellant, M5. If the ignition delay was shorter than 170 µs, it was hoped that uniform ignition might be achieved prior to the rupturing of the acetate centercore. The pressure time curves are given in Figure 6. Strong pressure waves were observed and are discussed in White et al. (1994). It can be seen that ignition delays are 250 µs or greater, long after the centercore has ruptured. Consequently, this design would lead to localized rear ignition and not give satisfactory ballistic performance, at least in this 30-mm test fixture.

5.2 Polyethylene, 1.6-mm (1/16 in) Wall Thickness. It became obvious that the 0.1-mm wall thickness acetate film would not be strong enough to prevent plasma energy from entering the rear of the charge at an early time. Using this in a high-loading density charge would probably result in localized (rear) ignition with subsequent pressure waves. As with the acrylic tube tests, it is clear that there is a strong axial pressure gradient in the flow that must be contained. A tubular polyethylene material was

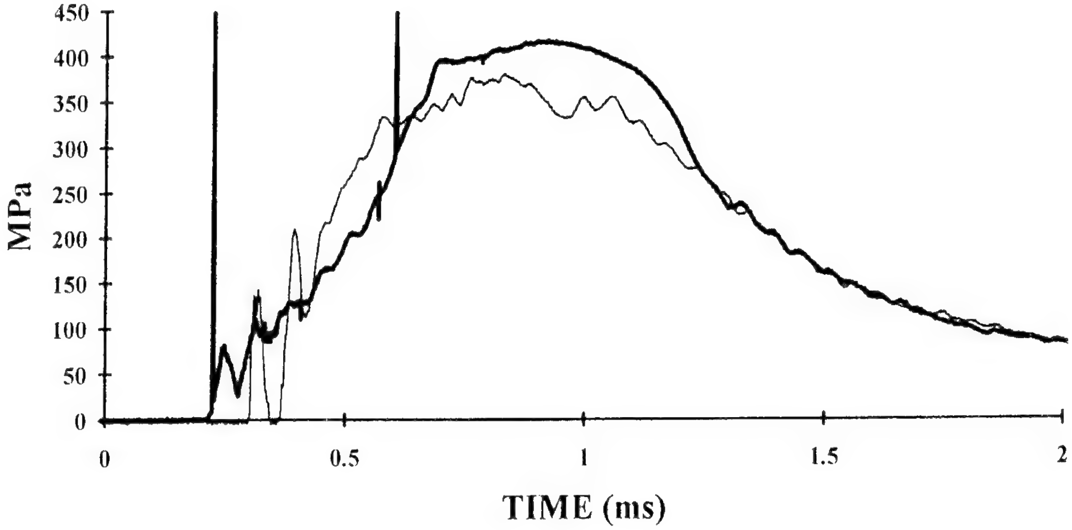


Figure 6. Pressure-time histories (P_1 dark, and P_2 light) for 30-mm firing (M5 granular propellant) using acetate centercore, ID 022693.

chosen as a compromise material. It has good toughness (wall thickness, 1.6 mm, 1/16 in) although the "milky" coloring causes radiation scattering, reducing the optical transparency of the material. To increase this transparency, four axial slits (at 0°, 90°, 180°, 270°) were cut along the length of the centercore at specific axial locations to enhance energy transmission at the most desirable areas when the centercore would be used in a propellant bed. The test conditions are listed in Table 4.

A number of configurations were used in an effort to eliminate the rupturing of the tube at the rear. The design evolved into the configuration shown in Figure 7. The rear section of the polyethylene tube is encased in a steel sleeve that affords added strength to that section of the tube. The four axial slits are placed forward of the steel sleeve and are located in approximately the center of the gun chamber. Photographic test results, along with power input and diode response, are shown in Figure 8 (the time between pictures is 70 µs). The steel sleeve at the left remains intact. The plasma output is clearly observed coming from the slits. As the power diminishes, so too does the radiation output, followed by an increase of both power and radiation at the 10th frame, 700 µs. As is seen from the power curve, at this time, the last stage of the PFN (Figure 3) is fired, accompanied by a large increase in light output. In a gun environment, the initial pulse is used to ignite the propelling charge and the last stage at 700 µs would occur later in the ballistic cycle and would be used to boost the chamber pressure and mass generation rate of the high-loading density charge.

Table 4. Polyethylene Centercore

ID	Centercore OD (mm)	Centercore thickness (mm)	Centercore length (mm)	Energy load (kJ)	Power peak (MW)	Comment, 1
050393,1	32	3.1	229	52	220	large pe tube uniform rupture
051193,2	12.5	1.6	178	49.6	186	1/2 pe, high E, 180 μs, end held
051293,1	12.5	1.6	178	48.7	211	repeat of above
051293,2	12.5	1.6	178	47.9	180	repeat but rear rupture
051393,1	12.5,Al	1.6	178	50.8	224	reduce radiation with Al/mylar
072093,1	12.5 re pe	1.6+1.6	178	51.7	279	microswitch; tube moved @ 2 ms; reinforce no help; diodes deviate @ 435 μs
082393,1	12.5 re pe	1.6+1.6	215+pe89	40.5	91	pe w 3.5 in pe reinforce; still ruptured
082493,1	12.5 re gl	1.6+3.1	215+gl89	41	75	pe w 3.5 in f-glass rein; held ok
082693,1	12.5 re pe	1.6+1.6	241+pe89	41.7	95	pe w 3.5 in pe rein; 1/4-in plasma; better lasted 70 μs longer
090293,1	12.5 re Fe	1.6+0.8	203+Fe89	43	97	pe w slits & 3.5 in steel reinf tube held, pe slits ok
091693,1	12.5 re Fe	1.6+0.8	206+Fe89	40.7	91	pe/Fe cc with 3/8 plasma; FMC ok

This centercore was used in the 30-mm gun and the pressure time curve is shown in Figure 9. It is seen that the forward pressure gage, P_2, increases prior to the rear gage, P_1. The reverse was true when the acetate centercore was used (see Figure 6). This dissimilarity indicates that the new configuration has moved the ignition further forward in the bed, even possibly causing ignition towards the base of the

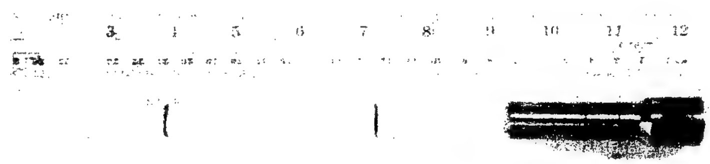


Figure 7. Slotted polyethylene centercore with steel reinforcement.

projectile. Pressure waves are still observed and are likely due to the sensitivity of the charge configuration. In particular, the very large length-to-diameter ratio of the chamber (7/1) and the high mass generation rate of the specific propellant used in this test can lead to such sensitivity. (This issue is discussed in Stobie et al. [1993]). The pressure is seen to rise at approximately 270 μs, which would be at the fourth frame in Figure 8.

6. 30-mm SIMULATOR

The open-air testing of the various centercore configurations established the general time sequence of events for the plasma injection process. The next step in understanding the ETC process was to examine the interaction of the plasma output with the propelling charge under conditions that more closely simulate the gun environment. As a consequence, a 30-mm gun simulator with an optical access port was used to examine the interaction of the plasma output with the propellant configuration. A photo of the setup using an acrylic chamber (length, 152 mm, ID, 38 mm) is given in Figure 10a. The plasma generator is on the left. The forward retaining plate on the right also acts as a short gun tube for the projectile that is inserted into a 30-mm hole in the plate (thickness, 12 mm). A later design used a steel chamber with a 25-mm-wide optically clear epoxy window (Figure 10b). The interior dimensions of the chamber are identical to those of the 30-mm gun fixture (ID = 32 mm, length = 216 mm). Two pressure gage ports are located at 38 mm from the rear and forward ends of the chamber, as in the 30-mm gun fixture (Stobie et al. 1993).

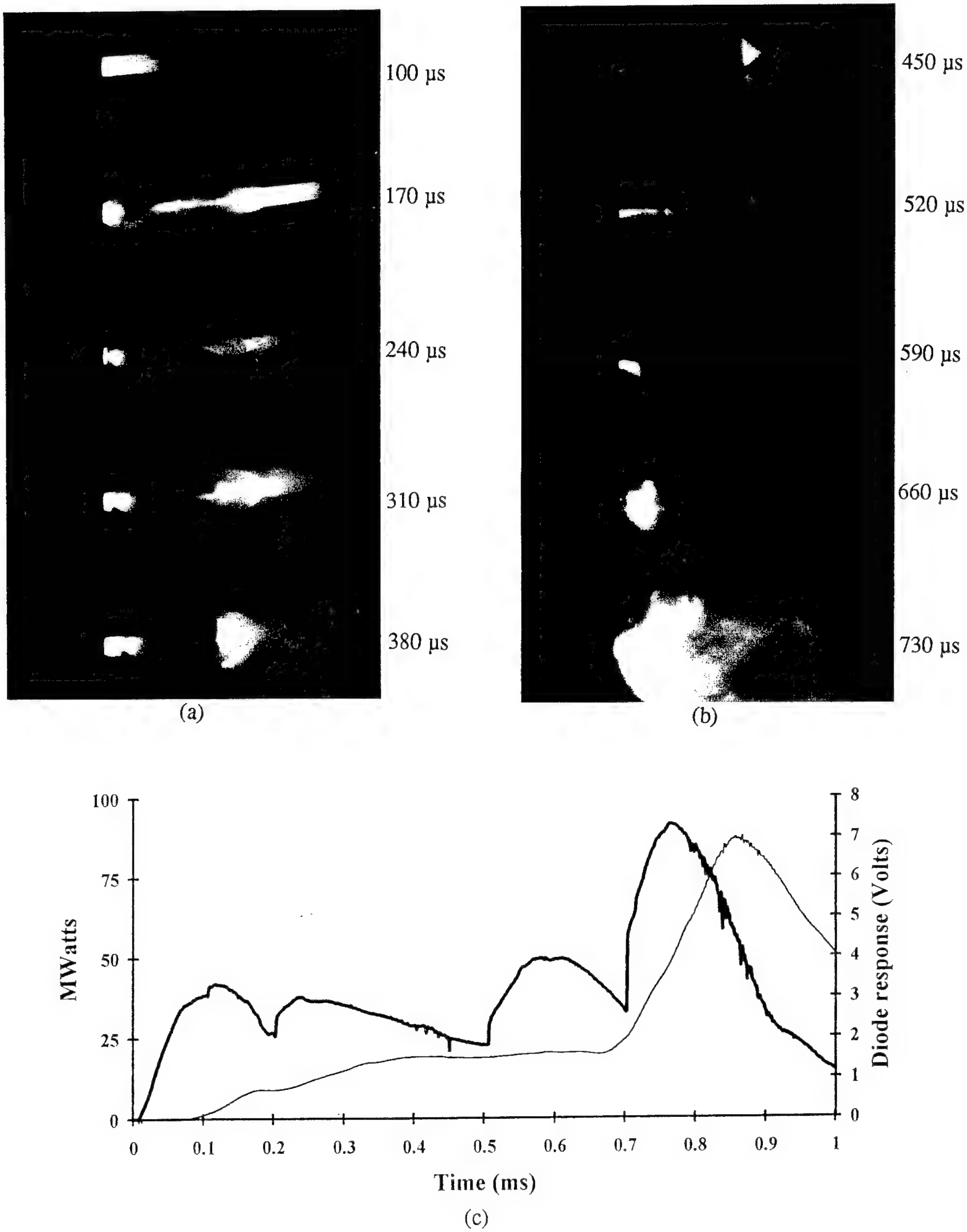


Figure 8. Polyethylene/steel centercore, ID 091693, (a) 14,000 pps, frames 1–5, (b) frames 6–10, (c) plasma power and diode response vs. time.

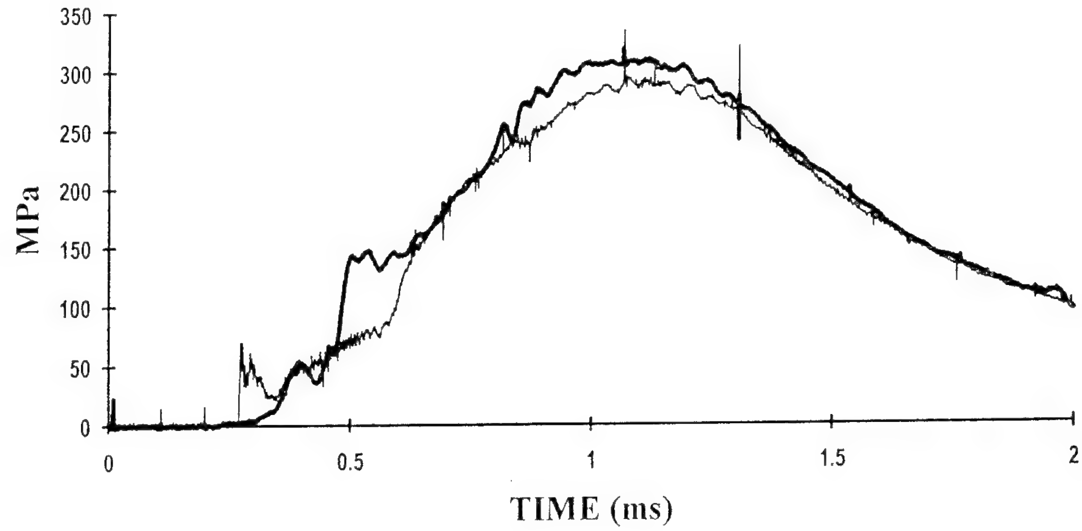
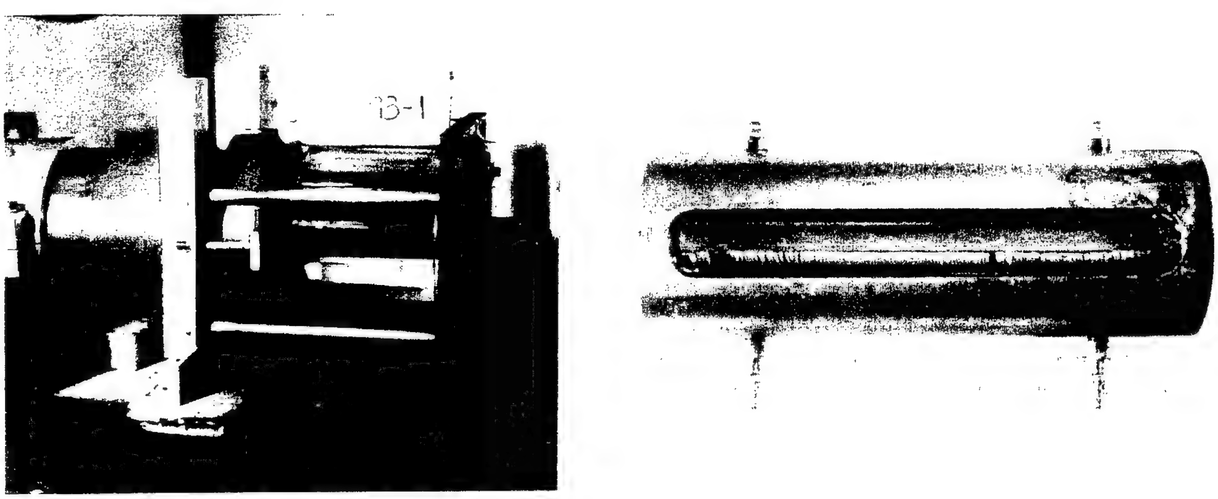


Figure 9. Pressure-time histories (P_1 dark, and P_2 light) for 30-mm firing (M5 granular propellant) using polyethylene/steel centercore, ID 092292-1.



(a) (b)

Figure 10. (a) 30-mm simulator, acrylic chamber; (b) steel chamber with epoxy window.

Some tests were carried out with a mix of granular inert and M5 propellant. Other tests were performed using the inert and live (JA2) disc propellant (Robbins et al. 1993). This configuration of propellant (OD = 30 mm, ID = 12.5 mm, web = 1.4 mm) was chosen since it can be "stacked" together to reach very high loading densities. For conventional chemical ignition charges, it may be difficult to achieve the potential performance of this charge design since the propellant may not be completely consumed prior to muzzle exit. However, with the introduction of electrical energy near or beyond peak pressure, it may be possible to maintain a constant pressure and increase the burn rate to extract more of the propellant energy than is possible with conventional ignition. Thus, investigation of the interaction of the plasma with this propellant geometry becomes very important.

Charges were constructed with several centercore designs with a mixture of the JA2 discs and inert (cardboard) discs (Figure 11). In Figure 11, a steel-sleeved polyethylene centercore was used. The dark rings indicate location of the live JA2 propellant discs. A slot was cut radially into the charge and an acrylic window was inserted so that the functioning of the centercore and interaction with the propellant could be observed. The charge assembled in the chamber is shown in Figure 10b. A summary of the data is shown in Table 5.

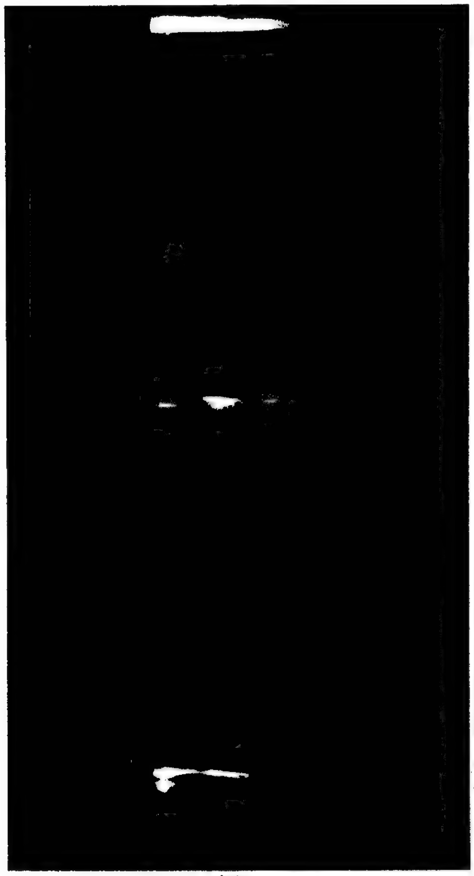
Two test results will be discussed. For test 081193, a slotted (nonreinforced) polyethylene centercore was used. The results are shown in Figure 12. As was seen in the open-air tests, the tube ruptures at the rear (800 μs), causing ignition of the propellant at the rear of the chamber. This coincides with the increase in power when the last stage on the PFN is fired. Only the rear propellant discs ignited. The discs in the middle and at the front were recovered, unburned. Post-firing examination of the polyethylene centercore also showed that the tube ruptured at the rear.

For test 091493, the steel-sleeved polyethylene centercore was used (Figures 7 and 11). The results of the simulator test are shown in Figure 13. Ignition of the ***central*** grains took place at approximately 600 μs. The power curve is similar to that in Figure 12. It appears then that the steel-reinforced polyethylene centercore reduces the likelihood of rear ignition of the charge and is a good candidate as an igniter tube for the 30-mm fixture.

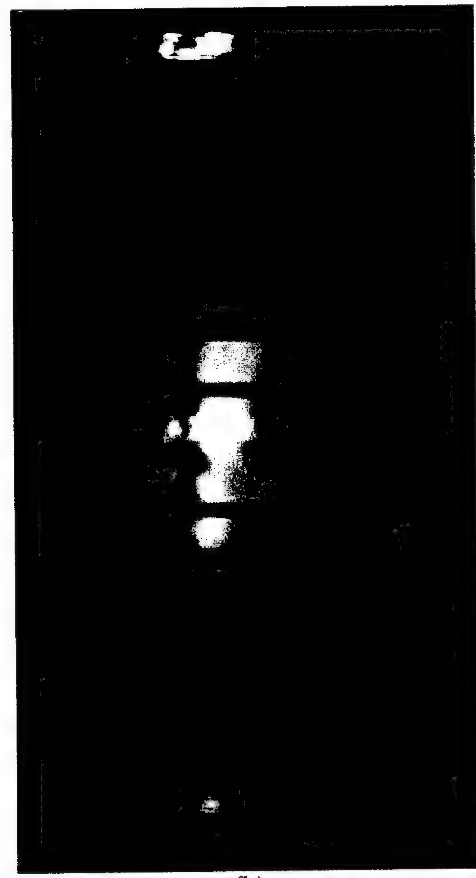
Table 5. 30-mm Simulator Tests

ID	Centercore			Energy	Power	Comments
	OD (mm)	Thickness (mm)	Length (mm)	Load (kJ)	Peak (MW)	
052193,1	12.5 pe	1.6	140	47	222	simulator 6x6x1 1/2, empty
052693,1	12.5 ace	0.1	140	11.3	36	simulator 6x6x1 1/2, mostly cardboard, proj
052793,1	12.5 pe	1.6	25	51	207	simulator 6x6x1 1/2, most card, 4 JA2, proj
081193,1	12.5 pe with 1 in pe	1.6+1.6	216+25 pe	42.4	86	30-mm sim, disc iner/live, back burned p strange, long pulse
081793,1	12.5 pe with 1 in pe	1.6+1.6	216+25 pe	42.7	95	30-mm sim, gran iner/live, rear ig p strange, long pulse, small proj move
090793,1	12.5 pe 3.5 Fe, 1/32	1.6+0.8 Fe	209+89 Fe	39	74	30-mm sim, gran/inert/liv center ig pe cc w steel reinf, no p,
091493,1	12.5 pe 3.5 Fe, 1/32	1.6+0.8 Fe	206+89 Fe	39	70	30-mm sim, disc inert/live, center ig slits at center prop only

Figure 11. Inert/JA2 disc charge with steel/polyethylene centercore and viewing window.



(a)



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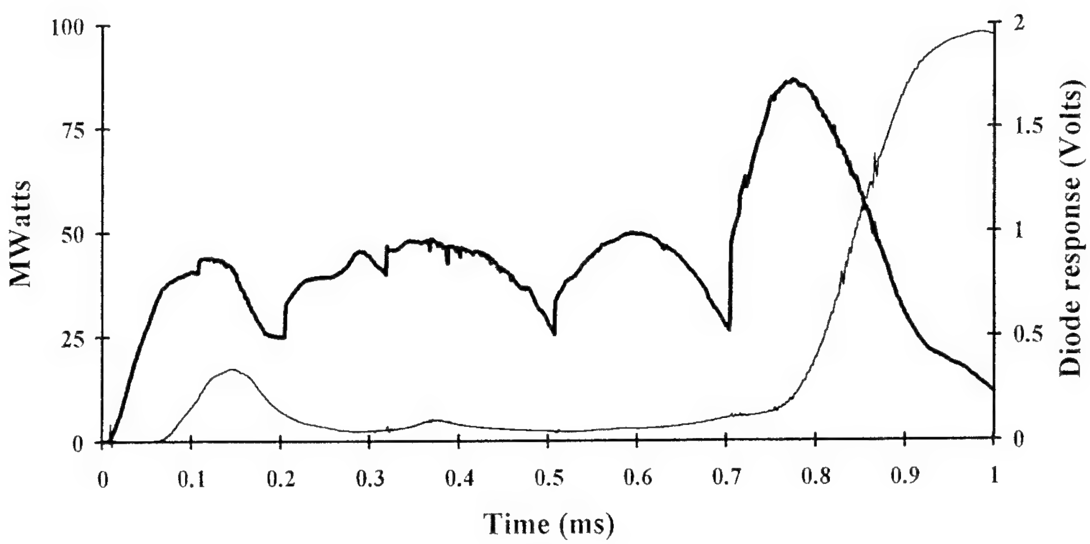
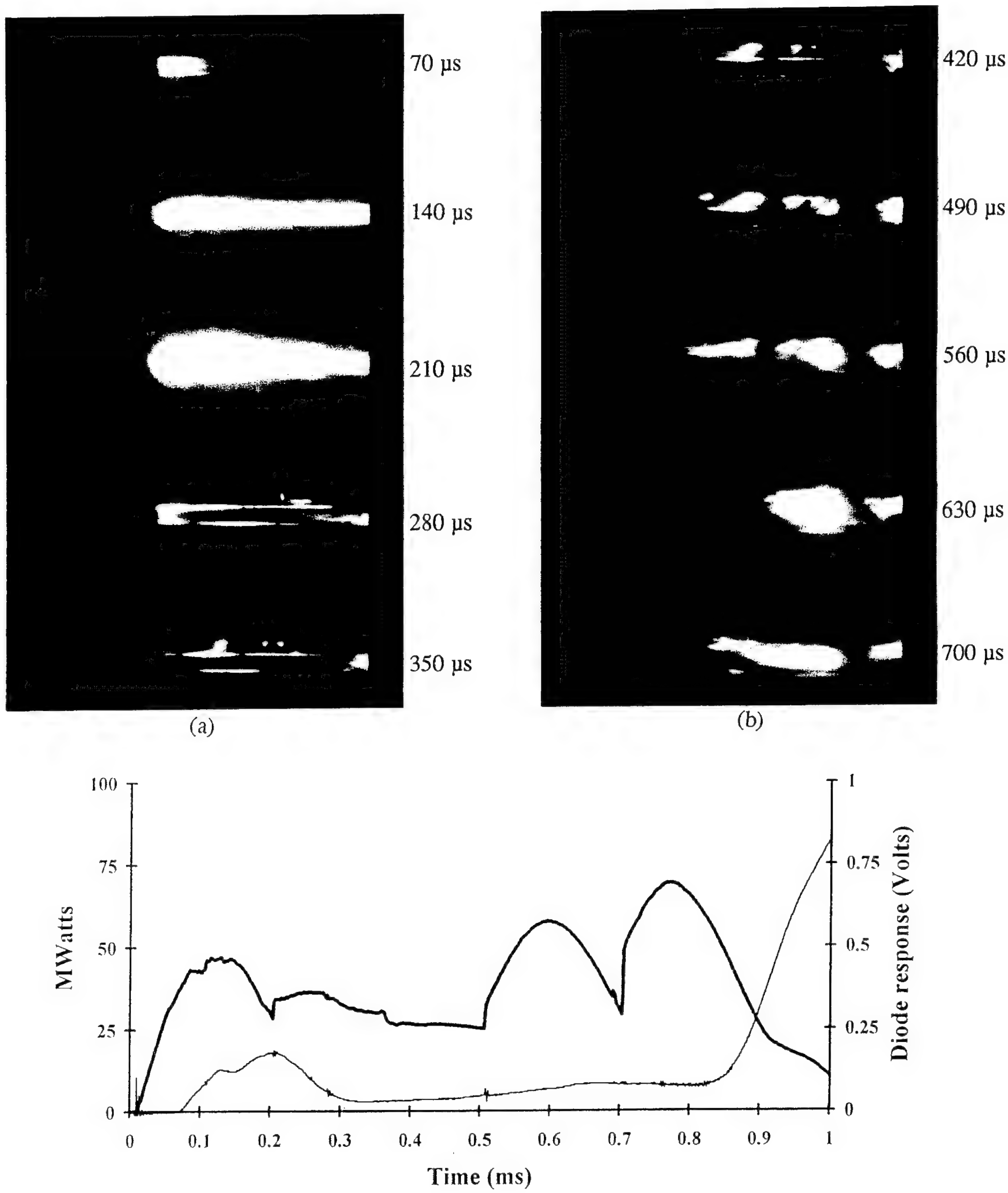


(c)

Figure 12. 30-mm simulator, polyethylene centercore, ID 081193, (a) 5,000 pps, frames 1–3, (b) frames 4–6, (c) plasma power and diode vs. time.



(c)

Figure 13. 30-mm simulator, polyethylene/steel centercore, ID 091493, (a) 14,000 pps, frames 1–5, (b) frames 6–10, (c) plasma power and diode vs. time.

7. CONCLUSIONS

The following general conclusions can be drawn from the tests described in this report that were conducted on different centercore configurations:

- Open-air free plasma firings exhibit the typical underexpanded jet formation patterns.

- The radiation component of the plasma is much greater than for a chemical igniter. Its role in ignition has not been clarified.

- Propagation velocity down the centercore is on the order of 1,800 m/s.

- Large axial pressure and energy gradients exist in the centercores. This must be considered when designing practical systems.

Future plans involve scaling up the centercore and simulator tests for larger caliber application. Ultimately, the ETC concept will be applied to tank or artillery-type guns for performance improvement. The methodology and techniques described here will be used to evaluate large-scale centercore concepts.

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13. ABSTRACT ***(Maximum 200 words)***

Successful application of the electrothermal chemical (ETC) propulsion concept will require an understanding of the propagation and interaction of plasmas in propellant beds. This information is necessary to exploit the ignition and combustion control that is possible with plasmas. Toward this end, an experimental program was designed to gain an understanding of the functioning of the plasma and the interaction of the plasma with the propelling charge, and finally a series of 30-mm gun tests, incorporating the experience gained in the first two parts of the program, was conducted.

This report describes the results of the first two parts of this program. Here results are described of tests on different igniter centercore configurations to be used for distributing the electrical plasma within the combustion chamber. High-speed photographic measurements were made of open air firings (with various centercore designs) and in a 30-mm gun simulator. Propagation velocities along with the time-sequence of events for the functioning in the centercore tubes were recorded. High axial pressure gradients were observed, necessitating mechanically robust centercores. Radiation levels substantially in excess of conventional igniters were also noted. These observations were exploited in the design of a plasma distribution centercore for 30-mm gun tests.

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